US006657518B1

(12) **United States Patent**
Weller et al.

(10) **Patent No.: US 6,657,518 B1**
(45) **Date of Patent: Dec. 2, 2003**

(54) **NOTCH FILTER CIRCUIT APPARATUS**

(75) Inventors: **Thomas M. Weller**, Lutz, FL (US); **Matthew C. Smith**, Largo, FL (US); **James W. Culver**, Seminole, FL (US)

(73) Assignee: **Raytheon Company**, Lexington, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/164,949**

(22) Filed: **Jun. 6, 2002**

(65) **Prior Publication Data**

(65)

(51) **Int. Cl.**^{7} **H01P 1/203**

(52) **U.S. Cl.** **333/204**; 333/202; 333/33; 333/133; 385/131; 385/129; 257/453; 257/76; 257/245

(58) **Field of Search** 333/202, 204, 333/33, 189, 133; 257/453, 76, 751, 245; 385/129, 14, 131

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,796,906	A	*	8/1998	Narayanan et al.	385/129
5,894,538	A	*	4/1999	Presby	385/129
5,966,478	A	*	10/1999	Marcuse et al.	385/14
6,100,775	A	*	8/2000	Wen	333/33
6,225,878	B1	*	5/2001	Takahashi et al.	333/204
6,307,450	B2	*	10/2001	Takahashi et al.	333/204
6,539,253	B2	*	3/2003	Thompson et al.	607/2

* cited by examiner

Primary Examiner—Michael Tokar
Assistant Examiner—Lam T. Mai
(74) *Attorney, Agent, or Firm*—Baker Botts L.L.P.

(57) **ABSTRACT**

According to one embodiment of the invention, a notch filter circuit includes a coplanar waveguide that includes a silicon substrate and at least one shunt stub bent at an angle to the coplanar waveguide. The notch filter circuit also includes at least one capacitor bridging at least one discontinuity of the shunt stub.

17 Claims, 3 Drawing Sheets

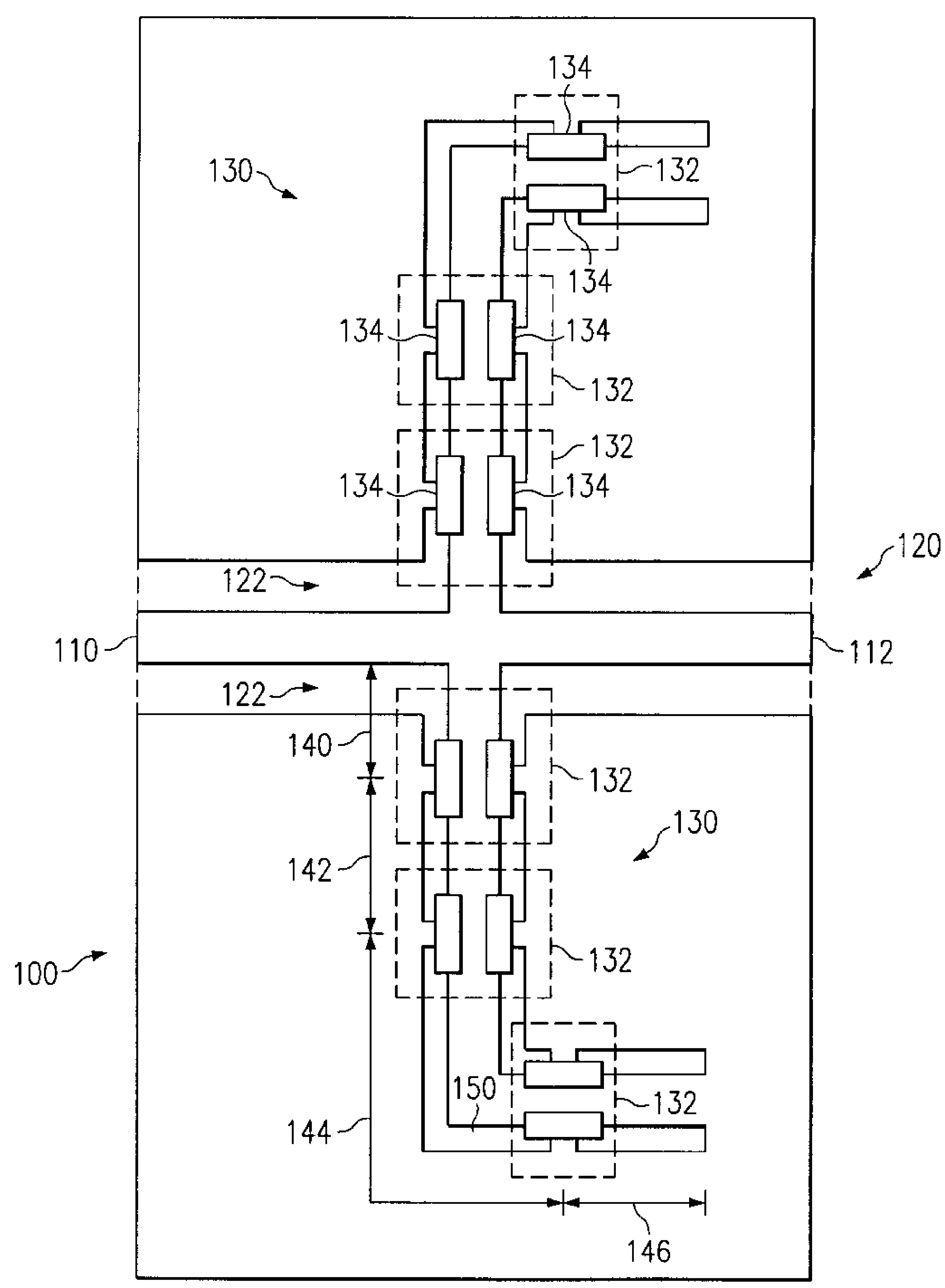
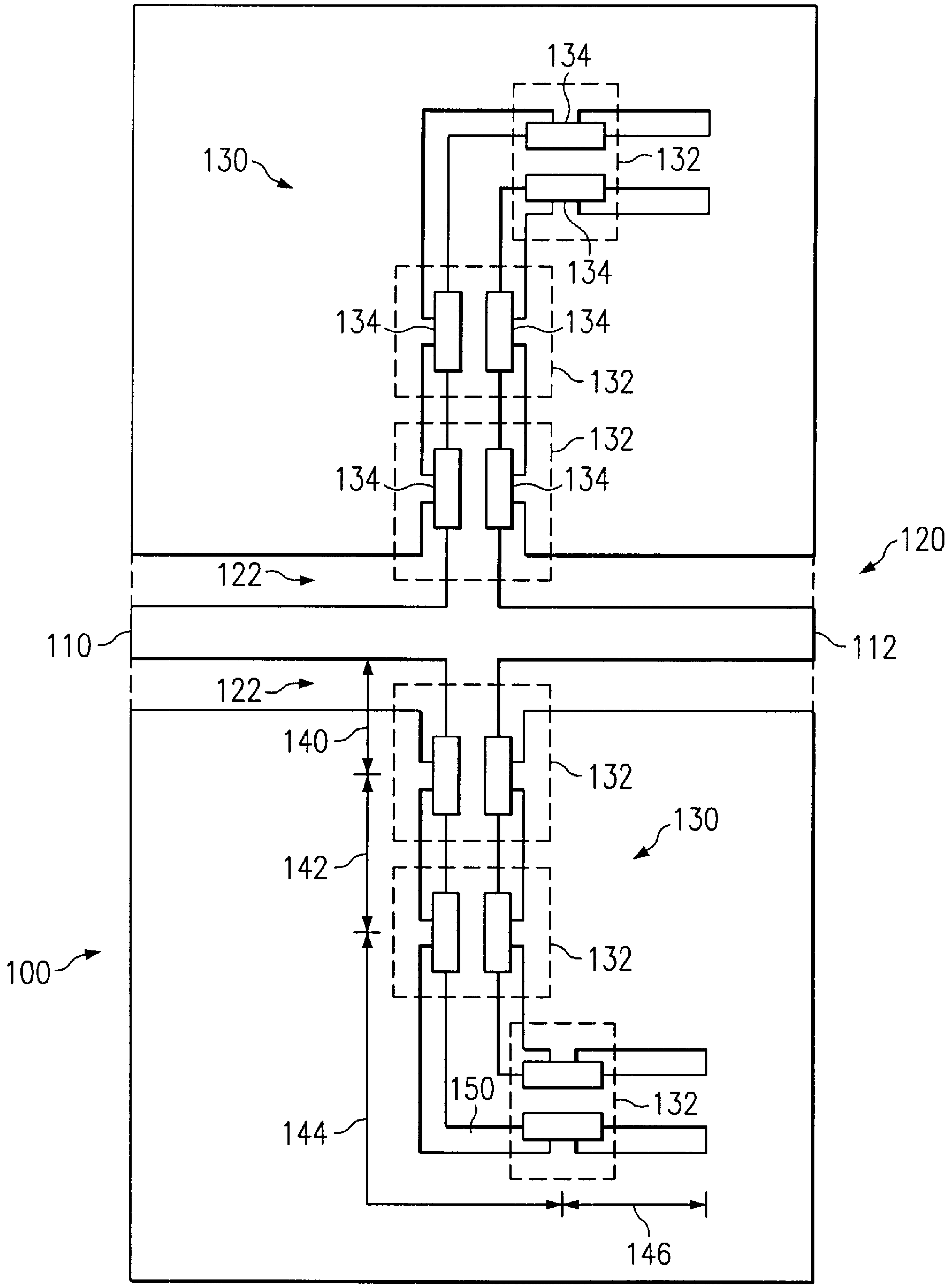


FIG. 1


134
130
132
134
134
134
132
132
134
134
120
122
110
112
122
140
132
130
142
132
100
150
132
144
146

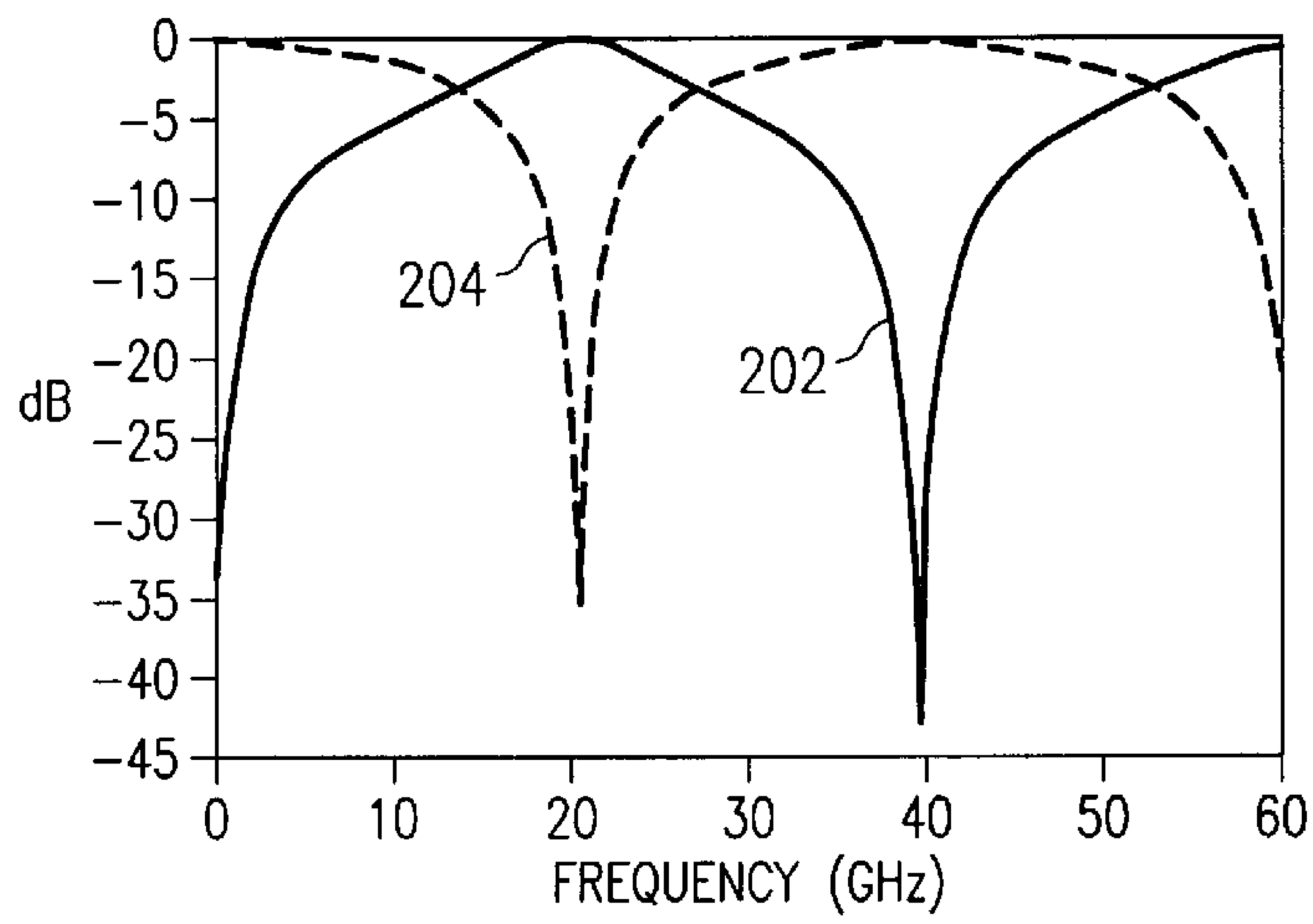


FIG. 2

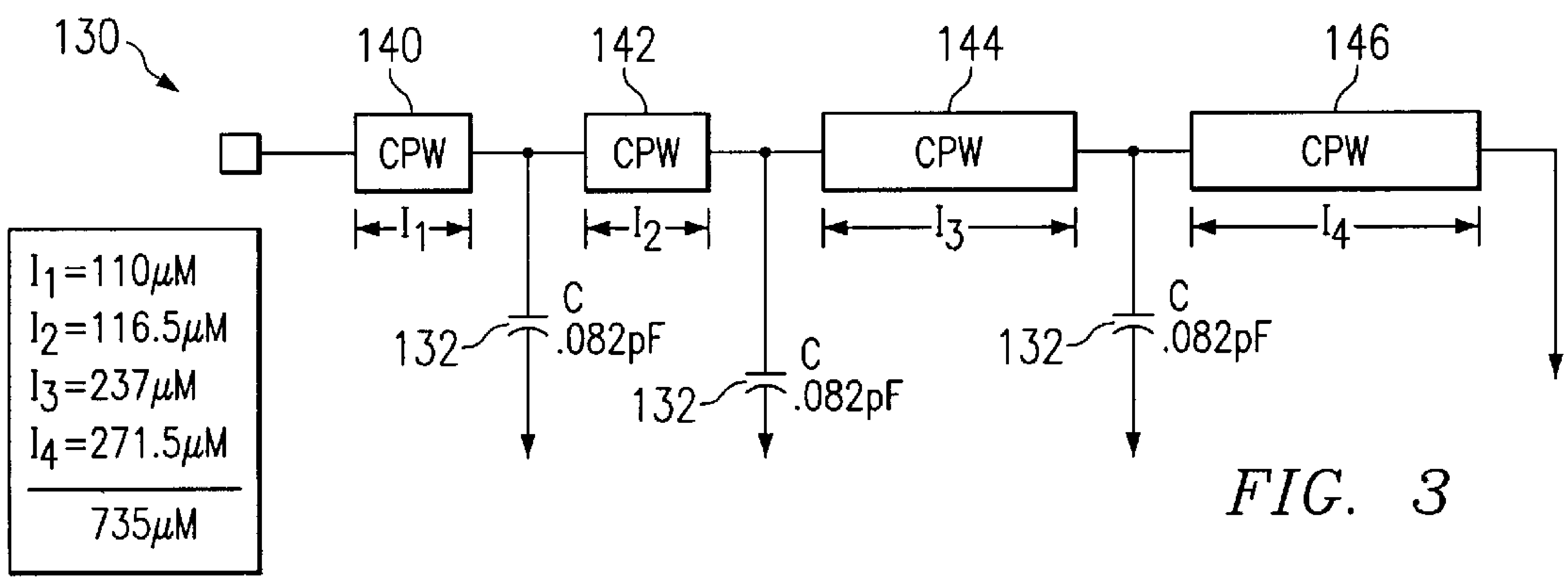


FIG. 3

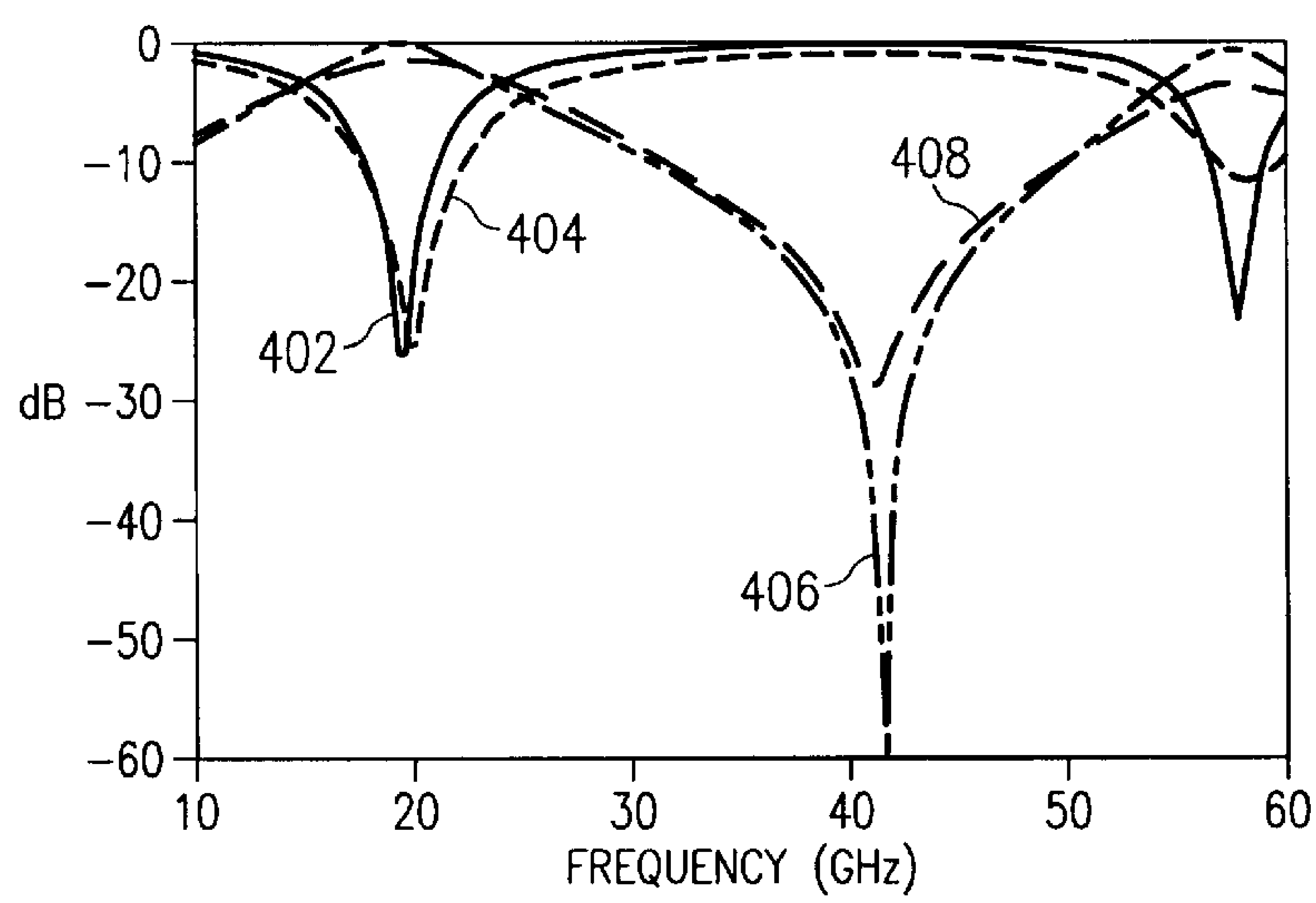


FIG. 4

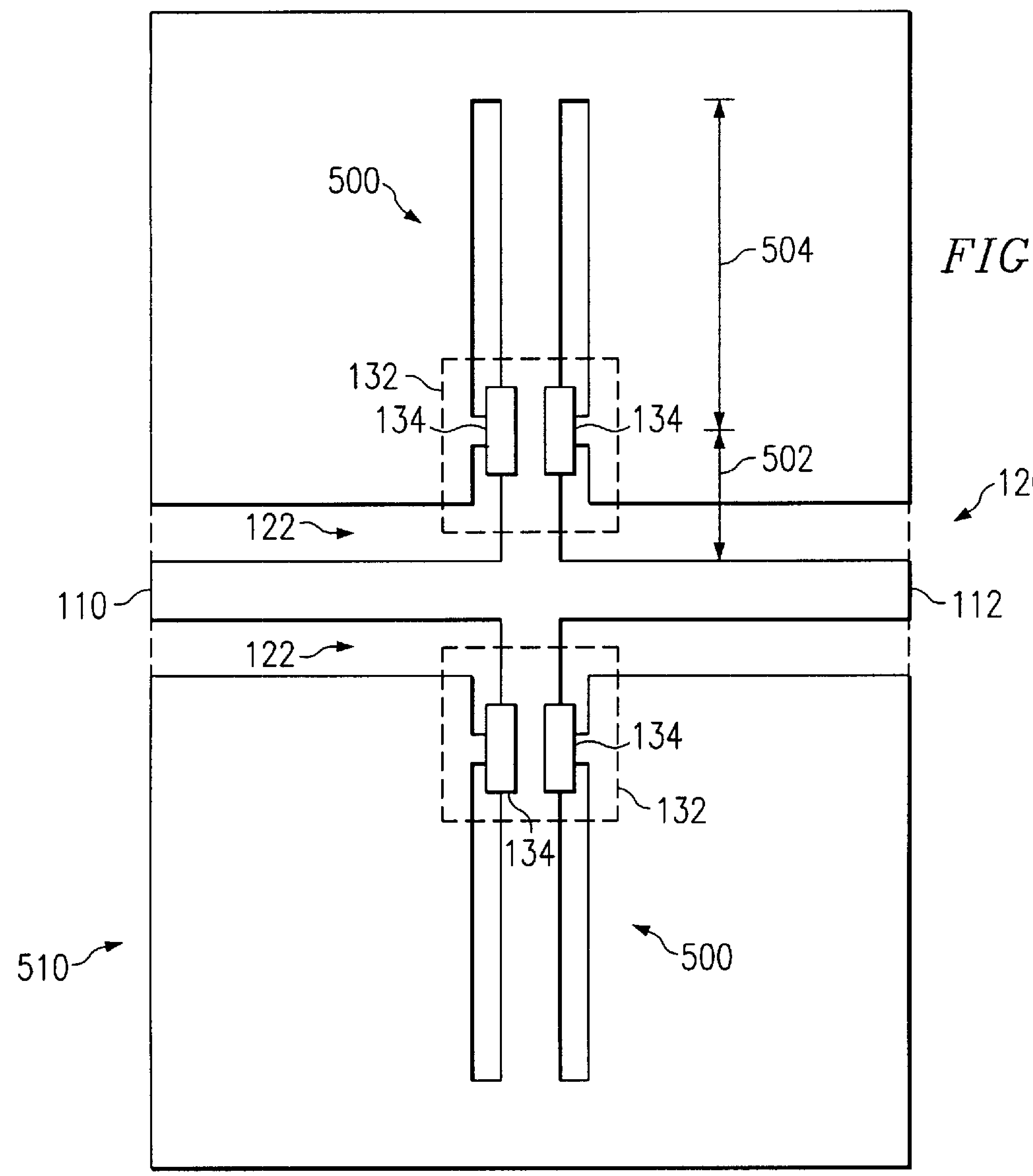

500
504
132
134
134
502
120
122
110
112
122
134
132
134
510
500

FIG. 5

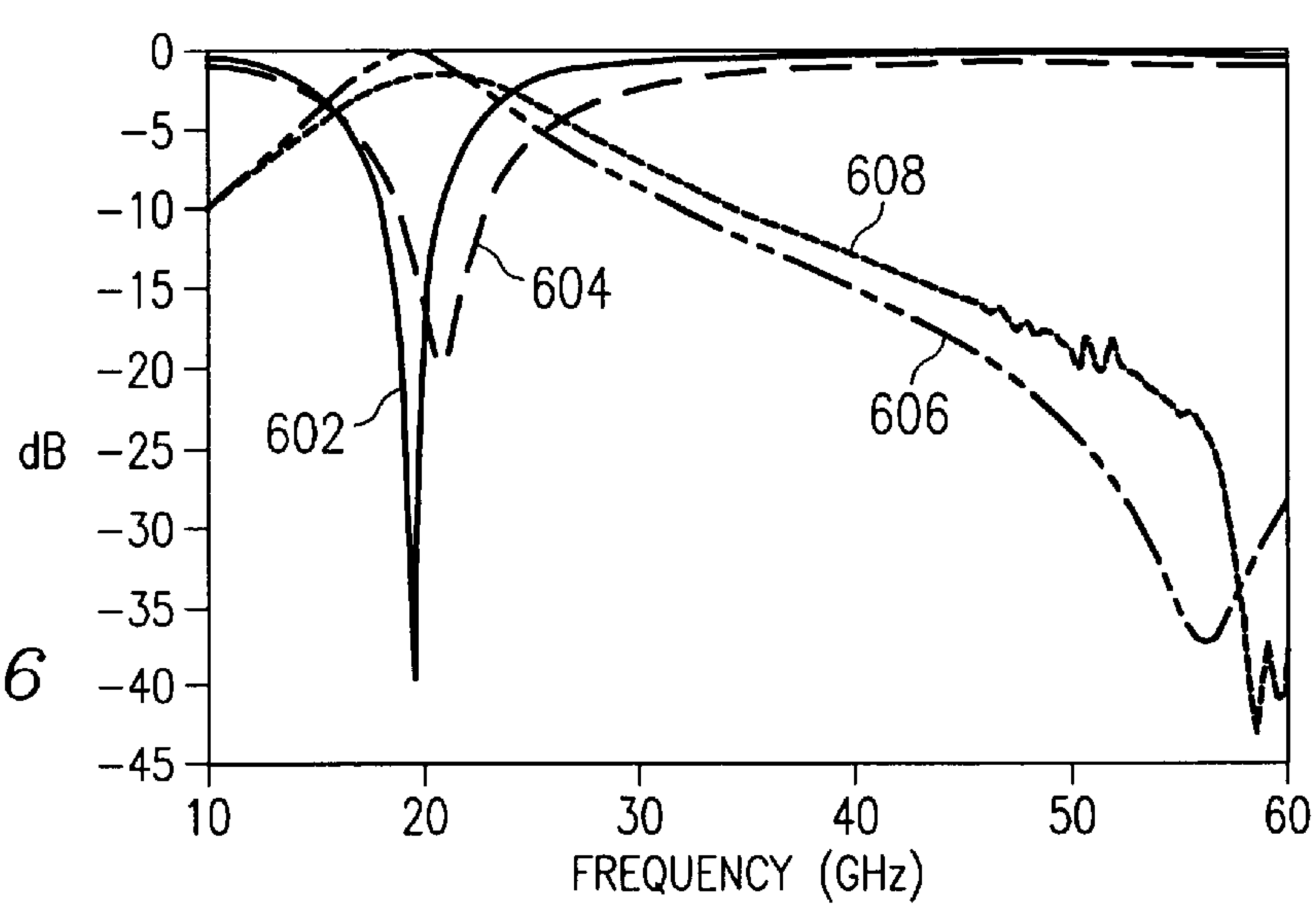

0
-5
-10
-15
-20
dB -25
-30
-35
-40
-45
10
20
30
40
50
60
FREQUENCY (GHz)
608
604
602
606

FIG. 6

NOTCH FILTER CIRCUIT APPARATUS

TECHNICAL FIELD OF THE INVENTION

This invention relates generally to filters and more particularly to a notch filter circuit apparatus.

BACKGROUND OF THE INVENTION

In many circuits it is desirable to operate the circuit so that one frequency signal is highly attenuated, while a desired frequency signal is left unattenuated. A circuit input, for example, may include not only a fundamental frequency signal, but may also include second, third, fourth, and higher harmonic frequency signals. In some circuit implementations it may be required to pass the fundamental frequency signal while blocking a specific harmonic signal. A notch, or bandstop, filter is the most appropriate filter to meet this requirement. A bandpass filter that discriminates against a wide range of frequency signals outside the passband may not provide the desired results.

Notch filters are often realized using distributed transmission line stubs, which can occupy significant substrate space. In conventional coplanar waveguide circuits, a notch filter may be created by symmetrically placing shunt stubs on opposite sides of the coplanar waveguide line. Conventional methods for reducing stub length, and therefore scarce substrate space, include using bent shunt stubs, meander structures, or capacitive loading. Notch filters employing these methods may be difficult to control over a broad frequency band or in more than one narrow frequency band of interest.

SUMMARY OF THE INVENTION

According to one embodiment of the invention, a notch filter circuit includes a coplanar waveguide that is located on a silicon substrate and at least one shunt stub bent at an angle to the coplanar waveguide. The notch filter circuit further includes at least one capacitor bridging at least one discontinuity of the shunt stub.

Some embodiments of the invention provide numerous technical advantages. Other embodiments may realize some, none, or all of these advantages. For example, according to one embodiment, a notch filter circuit utilizes at least one metal-insulator-metal capacitor in place of an air bridge or wire-bond to reduce the physical size of the notch filter. In some embodiments, the metal-insulator-metal capacitor also provides coplanar waveguide ground equalization. In addition the notch filter circuit may be implemented on a high-resistivity silicon substrate. In some embodiments, multiple metal-insulator-metal capacitors are located at specific positions along the length of stub to allow the filter pass-band and stop-band to be properly selected.

Other advantages may be readily ascertainable by those skilled in the art from the following FIGURES, description, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and the advantages thereof, reference is now made to the following description taken in conjunction with the accompanying drawings, wherein like reference numbers represent like parts, and which:

FIG. **1** illustrates a notch filter circuit in one embodiment of the present invention;

FIG. **2** graphically illustrates a simulated signal transmission curve and a simulated signal reflection curve for a conventional notch filter circuit containing air bridges;

FIG. **3** illustrates a schematic diagram of a notch filter circuit in one embodiment of the present invention;

FIG. **4** graphically illustrates signal transmission curves and signal reflection curves for a notch filter circuit in one embodiment of the present invention;

FIG. **5** illustrates a notch filter circuit that contains one metal-insulator-metal capacitor located in a straight shunt stub; and

FIG. **6** graphically illustrates signal transmission curves and signal reflection curves for a notch filter containing one metal-insulator-metal capacitor located in a straight shunt stub.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS OF THE INVENTION

Embodiments of the invention are best understood by referring to FIGS. **1** through **6** of the drawings, like numerals being used for like and corresponding parts of the various drawings.

FIG. **1** is a diagram illustrating a notch filter circuit **100** in one embodiment of the present invention. Notch filter circuit **100** includes an input port **110** and an output port **112**. Notch filter circuit **100** also includes a Coplanar Waveguide (CPW) **120** located on a substrate **122**. Notch filter circuit **100** further includes at least one shunt stub **130**. In one embodiment of the present invention, notch filter circuit **100** includes two symmetrical shunt stubs **130** located on opposite sides of CPW **120**.

CPW **120** may be formed by placing metal layers (the light regions of FIG. **1**) on a substrate **122** (the dark regions of FIG. **1**). In one embodiment of the present invention, CPW **120** is formed from chromium-silver-chromium-gold (Cr—Ag—Cr—Au) metal layers total thickness, approximately one micron (μm); however, a CPW **120** formed from any suitable material and dimension is within the scope of the present invention. CPW **120** is formed by placing the metal layers on a silicon substrate **122**, which in one embodiment is highly resistive. In one embodiment the silicon substrate is approximately 400 μm thick. Shunt stub **130** may also be formed by placing Cr—Ag—Cr—Au metal layers on silicon substrate **122**. A shunt stub **130** formed from any suitable material is within the scope of the present invention. In one embodiment of the present invention, shunt stub **130** will be patterned in the same plane as CPW **120** and bent at an angle of ninety degrees relative to the longitudinal axis of CPW **120**. Other configurations of shunt stub **130** may also be utilized. Shunt stub **130** includes at least one metal-insulator-metal (MIM) capacitor **132** located at a discontinuity of shunt stub **130**; however, other types of capacitor **132** are within the scope of the present invention.

In one embodiment, symmetrical shunt stubs **130** are located on opposite sides of CPW **120**. Input port **110** of notch filter circuit **100** is operable to receive an incoming microwave or millimeter-wave electronic signal and direct the signal into CPW **120**. Shunt stubs **130** filter the signal, and the filtered signal will be output from CPW **120** at output port **112**. For purposes of illustration shunt stubs **130** and CPW **120** are discussed as forming a notch filter circuit **100** operable to pass signals of 21 GHz and stop, or notch, signals of 42 GHz. For this example 21 GHz is the fundamental frequency signal, and 42 GHz is the second harmonic frequency signal. Notch filter circuit **100** may be designed to pass frequencies and to stop other particular frequencies, and it is envisioned that other notch filter circuits **100** so designed are also within the scope of the present invention.

In conventional shunt stub designs air bridges are placed at discontinuities within shunt stub **130** to suppress the propagation of undesired modes. A conventional shunt stub design locates air bridges where MIM capacitors **132** are located in notch filter circuit **100** of FIG. **1**. When properly designed with an adequate bridge-height and minimum bridge-width, the air bridge introduces minimal parasitic effects to the conventional notch filter circuit. Conventional notch filter circuits implemented using air bridges occupy significant surface area in a circuit design as will be described below in greater detail.

FIG. **2** graphically illustrates the response of a conventional notch filter circuit wherein each shunt stub **130** includes a first air bridge located a distance **140** from CPW **120**, a second air bridge located a distance **142** from the first air bridge, and a third air bridge located a distance **144** from the second air bridge and a distance **146** from the end of the conventional shunt stub. The air bridges of conventional notch filter circuits are not illustrated in FIG. **1** for reasons of clarity. In order to obtain a pass-band at a fundamental frequency and a stop-band at a second harmonic frequency, the total physical length of the conventional shunt stub is determined by dividing the guided wavelength of the fundamental frequency by four. Accordingly, in order to obtain a pass-band at 21 GHz and a stop-band at 42 GHz, the total physical length of the conventional shunt stub is approximately 1490 μm. Thus, distances **140**, **142**, **144**, and **146** add to a total distance of 1490 μm.

Referring now to FIG. **2**, there are graphically illustrated a simulated signal transmission curve **202** and simulated signal reflection curve **204** for a conventional notch filter circuit. An electromagnetically-simulated signal transmission curve **202** illustrates a high signal transmission at approximately 20 GHz and a very low signal transmission at approximately 40 GHz. An electromagnetically-simulated signal reflection curve **204** illustrates a high signal reflection at approximately 40 GHz and a very low signal reflection at approximately 20 GHz. Thus, a conventional notch filter circuit may be made to effectively pass a fundamental frequency signal while blocking a second harmonic frequency signal, although a conventional shunt stub length of 1490 μm is required.

According to the teachings of the invention, shunt stub **130** in one embodiment of the present invention is illustrated in FIG. **1** as including three MIM capacitors **132**. A first MIM capacitor **132** is located a distance **140** from CPW **120**, and a second MIM capacitor **132** is located a distance **142** from first MIM capacitor **132**. A third MIM capacitor **132** is located a distance **144** from second MIM capacitor **132** and a distance **146** from the end of shunt stub **130**. In one embodiment a silicon-oxide (SiO) layer 0.58 μm thick may be used as a dielectric **134** in MIM capacitors **132**. Any suitable material or thickness of dielectric is within the scope of the present invention. By using MIM capacitors, notch filter circuit **100** is operable to attenuate a selected frequency with little effect on other frequencies. In some embodiments of the present invention, multiple MIM capacitors **132** are located at specific positions along the length of shunt stub **130** to allow the pass-band and stop-band of notch filter circuit **100** to be properly selected.

FIG. **3** illustrates a circuit model equivalent of notch filter circuit **100** of FIG. **1**. In the illustrated embodiment MIM capacitors **132** are sized at 0.082 pF, and the locations of MIM capacitors **132** are indicated by distances **140**, **142**, **144**, and **146**. Through proper selection of shunt stub **130** parameters and MIM capacitor **132** values, it is possible to obtain an effective notch filter circuit **100** with a pass-band response at 21 GHz ($Z_{in,\ stub}$=infinity Ω) and a stop-band response at 42 GHz ($Z_{in,\ stub}$=0 Ω). $Z_{in,\ stub}$ is the shunt stub impedance with respect to a particular frequency signal. The total physical length of each shunt stub **130** in this embodiment is 735 μm. By replacing the air bridges with three MIM capacitors **132**, therefore, shunt stub **130** may be reduced in size from 1490 μm to 735 μm.

The required surface area for notch filter circuit **100** may be significantly reduced by replacing the conventional air bridges with MIM capacitors **132** in shunt stubs **130**. In microwave and millimeter-wave integrated circuits, compact layout is an important issue that is limited by both circuit cross-talk and component size. Filter size is particularly important, because the filters are often realized using distributed transmission line stubs that can occupy significant substrate space.

MIM capacitors **132** serve an additional function within notch filter circuit **100**. MIM capacitors **132** are, in one embodiment, operable to provide CPW **120** ground equalization through the underlying metal by providing a direct current contact between the two ground paths of CPW **120**. Ground equalization in conventional notch filter circuits has been accomplished using air bridges.

Referring now to FIG. **4** there is graphically illustrated a comparison between electromagnetic simulation results and the measured response of notch filter circuit **100** employing MIM capacitor-loaded shunt stubs **130**. A measured signal transmission curve **408** substantially matches the simulated signal transmission curve **406**. Similarly, a measured signal reflection curve **404** substantially matches the simulated signal reflection curve **402**. Measured signal transmission curve **408** illustrates a high signal transmission level at approximately 20 GHz and a low signal transmission level at approximately 40 GHz. Measured signal reflection curve **404** illustrates a high signal reflection level at approximately 40 GHz and a low signal reflection level at approximately 20 GHz. In one embodiment, the 3-dB pass-band bandwidth of notch filter circuit **100** is approximately 55 percent. The insertion loss is approximately 1 dB at 21 GHz and the rejection at 42 GHz is 30 dB. FIG. **4** illustrates that one embodiment of notch filter circuit **100** is operable to transmit a fundamental signal frequency and block a second harmonic frequency signal. Notch filter circuit **100** is operable to do so with shunt stubs **130** approximately 50 percent smaller than the shunt stubs in a conventional notch filter circuit.

Referring now to FIG. **5** there is illustrated a notch filter circuit **510** embodying a MIM capacitor-loaded straight shunt stub topology. In this embodiment a single MIM capacitor **132** is located in each straight shunt stub **500**. Neglecting parasitic effects, the impedance seen looking into straight shunt stub **500** is given by

$$Z_{in,stub} = \frac{jZ_0 \tan\theta}{1 - \omega C Z_0 \tan\theta}$$

In the equation ω is 2nf, where f is the frequency, C is the capacitance of MIM capacitor **132**, Z_0 is the characteristic impedance, and θ is the electrical length of shunt stub **500**. The above equation assumes that MIM capacitor **132** is located at the exact junction between CPW **120** and straight shunt stub **500**. This means MIM capacitor **132** is located a zero distance **502** from CPW **120**. To obtain the pass-band filter response at 21 GHz $Z_{in,\ stub}$=infinity Ω) a fixed C and Z_0 are used in the following equation:

$$\theta = \tan^{-1}\left(\frac{1}{\omega C Z_0}\right)$$

From this equation it is seen that θ decreases with increasing C, and θ will be less than 90° for any non-zero value of C. With C and Z_0 fixed however, it will not be possible to satisfy the filter stop-band response at the second harmonic frequency of 42 GHz ($Z_{in,\ stub}$=0 Ω), which requires θ to 180° .

An analysis of the circuit illustrated in FIG. **5**, in which distance **502** is allowed to be non-zero, reveals that a single MIM capacitor **132** in a straight shunt stub **500** is operable to provide the desired responses at the pass-band and stop-band frequencies. Since MIM capacitor **132** serves a dual purpose of capacitive-loading of CPW **120** and ground plane equalization, it is important that MIM capacitor **132** be placed near the junction between shunt stub **500** and CPW **120** in this embodiment. Therefore, distance **502** should be minimized to the extent possible. Decreasing distance **502** requires that the size of MIM capacitor **132** increase. In one embodiment of the present invention, the correct pass-band and stop-band responses were obtained in notch filter circuit **510** with distances **502** and **504** equaling 110 μm and 300 μm, respectively, and a MIM capacitor **132** value of 0.65 pF. By way of contrast, notch filter circuit **100** as illustrated in FIG. **1** required only MIM capacitors **132** sized at 0.082 pF. Parasitic effects in MIM capacitor **132** of size 0.65 pF become noticeable in the 40–60 GHz range, however, which complicates the process of establishing the null at the desired second harmonic frequency.

Referring now to FIG. **6**, there is graphically illustrated a comparison between a measured response and electromagnetic simulation results for a notch filter circuit **510** embodying the straight shunt stub topology. In this design distances **502** and **504** were 110 μm and 470 μm, respectively, and MIM capacitor **132** was sized at 0.275 pF. In FIG. **6** measured signal transmission curve **608** is similar to simulated signal transmission curve **606**. Measured signal reflection curve **604** is similar to simulated signal reflection curve **602**. Although not an optimal design for this application, the results illustrated in FIG. **6** demonstrate the presence of a controllable stop-band response at approximately 58 GHz.

Although the present invention has been described with several example embodiments, various changes and modifications may be suggested to one skilled in the art. It is intended that the present invention encompass those changes and modifications as they fall within the scope of the claims.

What is claimed is:

1. A notch filter circuit apparatus, comprising:

a coplanar waveguide located on a silicon-substrate;

at least one shunt stub; and

at least one capacitor bridging a discontinuity of the at least one shunt stub.

2. The apparatus of claim **1**, wherein the coplanar waveguide is comprised of a plurality of chromium-silver-chromium-gold metal layers.

3. The apparatus of claim **1**, wherein the silicon substrate comprises a high-resistivity silicon substrate.

4. The apparatus of claim **1**, wherein the at least one shunt stub is comprised of a plurality of chromium-silver-chromium-gold metal layers.

5. The apparatus of claim **1**, wherein the at least one shunt stub is bent at an angle to the coplanar waveguide.

6. The apparatus of claim **1**, wherein the at least one shunt stub is bent at an angle of ninety degrees to the coplanar waveguide.

7. The apparatus of claim **1**, further comprising a first shunt stub located on an opposite side of the coplanar waveguide from a second shunt stub.

8. The apparatus of claim **7**, wherein the first shunt stub is symmetrical with the first shunt stub about the coplanar waveguide.

9. The apparatus of claim **1**, wherein the at least one capacitor comprises a metal-insulator-metal capacitor.

10. A system for filtering an electrical signal, comprising:

a coplanar waveguide located on a silicon substrate;

a first shunt stub, with a bend of ninety degrees with respect to the longitudinal axis of the coplanar waveguide;

a second shunt stub, located on an opposite side of the coplanar waveguide, and symmetrical to the first shunt stub about the coplanar waveguide;

at least one metal-insulator-metal capacitor bridging a discontinuity of the first shunt stub; and

at least one metal-insulator-metal capacitor bridging a discontinuity of the second shunt stub.

11. The system of claim **10**, wherein the coplanar waveguide is comprised of a plurality of chromium-silver-chromium-gold metal layers.

12. The system of claim **10**, wherein the silicon substrate comprises a high-resistivity silicon substrate.

13. The system of claim **10**, wherein the first and second shunt stubs are comprised of a plurality of chromium-silver-chromium-gold metal layers.

14. A system for filtering an electrical signal, comprising:

a coplanar waveguide located on a silicon substrate;

a first shunt stub at a right angle to the coplanar waveguide;

a second shunt stub, symmetrical with the first shunt stub about the coplanar waveguide;

at least one metal-insulator-metal capacitor bridging a discontinuity of the first shunt stub; and

at least one metal-insulator-metal capacitor bridging a discontinuity of the second shunt stub.

15. The system of claim **14**, wherein the coplanar waveguide is comprised of a plurality of chromium-silver-chromium-gold metal layers.

16. The system of claim **14**, wherein the silicon substrate comprises a high-resistivity silicon substrate.

17. The system of claim **14**, wherein the first and second shunt stubs are comprised of a plurality of chromium-silver-chromium-gold metal layers.

* * * * *